Active tectonics of the Black Sea with GPS

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The Black Sea occurs within the Anatolian sector of the Alpine-Himalayan orogenic system. In this region northward moving African and Arabian plates collide with Eurasian plate. From this collision the Anatolian block moves westward with a rotation pole located approximately north of Sinai peninsula. Tectonic styles and rates in the circum Black Sea and along the Crimea have been poorly known. A GPS project was initiated in 1995 with the collaboration between Istanbul Technical University, MIT and Joint Institute of Physics of the Earth (Moscow). To carry out the project, two GPS campaigns were performed. Data have been analysed by the well-known GPS processing program, GAMIT which is a comprehensive GPS analysis package, and GLOBK, a Kalman filter. This paper presents the important outputs from the two GPS campaigns and gives suggestions for the future investigations in the region. The important outcome of the project is that the N-S motions along mostly in the Eastern margin of the Black Sea are in a few mm/year, such as SINO, a southern coast site, with a rate of 1.4 ± 1.7 mm/year in NW direction, and GELE, a northern coast site, with a rate of 2.2 ± 2.8 mm/year in SE direction, while the velocities in the Anatolian region are approximately $10–20 \pm 3–5$ mm/year.

1. Introduction

The Black Sea is one of the largest enclosed seas and has been in existence for the last 200 Ma. The Black Sea occurs within the Anatolian sector of the Alpine-Himalayan orogenic system and it is located between the Eurasian plate in the north and the African-Arabian plates in the south. Global plate models (DeMets *et al.*, 1990; DeMets *et al.*, 1994) and recent space geodetic measurements (Smith *et al.*, 1994; Reilinger *et al.*, 1997a) indicate that in the surrounding region northward moving the African and the Arabian plates collide with the Eurasian plate. From this collision the Anatolian block moves westward with a rotation pole located approximately in the north of the Sinai peninsula. Within this tectonic framework, the present-day tectonics of the Black Sea has been a puzzle.

The Global Positioning System (GPS) has become a very useful tool in the area of earth sciences because of its capability that provides high precision assessment of continental and regional deformation (Segall and Davis, 1997; Herring, 1999; Tari, 1999). In this paper, GPS observations collected in the Black Sea's surrounding area are taken into consideration in order to have information about the contemporary tectonic processes of the region.

2. Tectonic History

Geologically the Black Sea basin is divided into two parts, Western and Eastern, separated by the Mid Black Sea ridge (Figs. 1 and 2). The origin of the Black Sea has been long studied and is complicated in detail. The rifting age has been suggested as the Aptian-Albian period for the entire Black Sea (Gorur, 1997), nevertheless rifting age for the Eastern Black is less known (Spadini *et al.*, 1996). Following the closure of the Neothys the Black Sea began also to close in the Eocene-Oligocene time. The eastern Black Sea continued to close from Miocene up to present. On the other hand, the central and western Black Sea has more complicated neotectonics influenced by all, escape of the Anatolian block, northward motion of the African plate and the Aegean extension.

Seismic activity within the circum Black Sea is assumed as low-moderate for this century. The western end of the Black Sea, north of the Marmara Sea, Bulgaria, Romania and Ukraine should be influenced by extensional tectonics in the Western Turkey and Aegean. There is a speculation that the lithosphere of the Black Sea and Caspian Seas form a resistant "backstop" diverting the impinging Anatolian plate to the west and "funneling" the continental lithosphere of eastern Turkey and the Caucasus around the eastern side of the Black Sea (McClusky *et al.*, 2000).

3. Black Sea GPS Campaigns

GPS measurements in the Black Sea region were collected as parts of different projects, some of which are still in progress (McClusky *et al.*, 2000; Tari, 1999). As part of these projects eastern and western Turkey were observed between 1988 and 1992 with sufficient overlap to allow integration of networks, but since the 1994 survey almost all of the stations were occupied during each survey (Reilinger *et al.*, 1997b; Tari, 1999). Although some of sites in Bul-

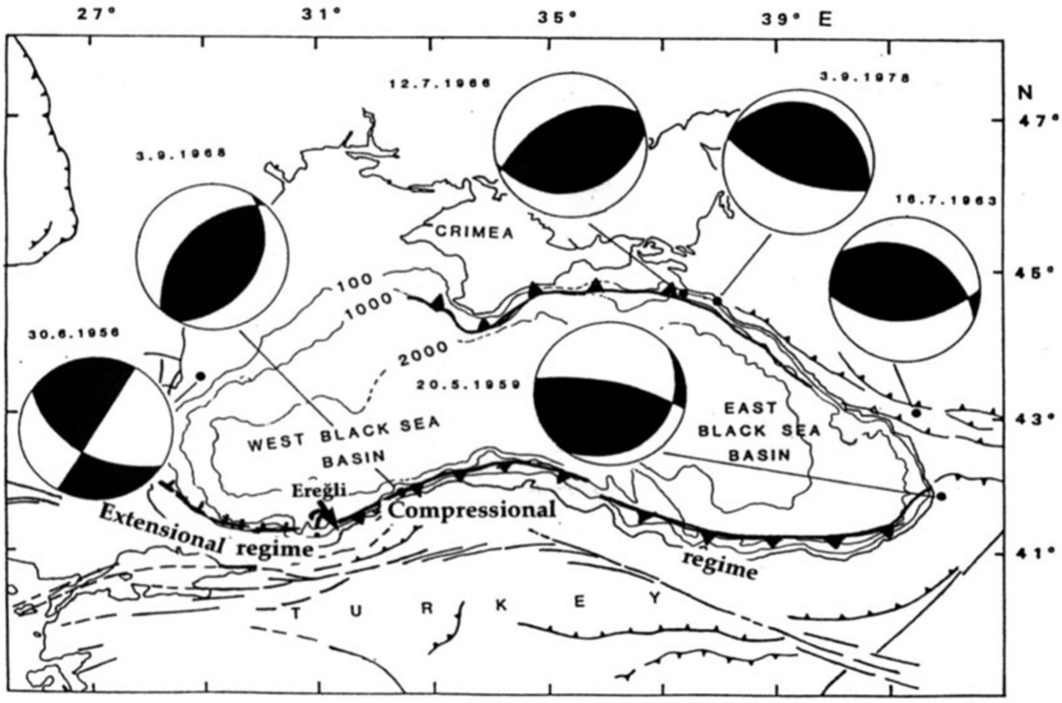

Fig. 1. Tectonics of the Black Sea (from Barka and Reilinger, 1997). Most of the southern and northern margins show shortening, except north of the Marmara Sea region (west of the 31°E) and Bulgarian and Romanian coasts which are in the extensional nature.

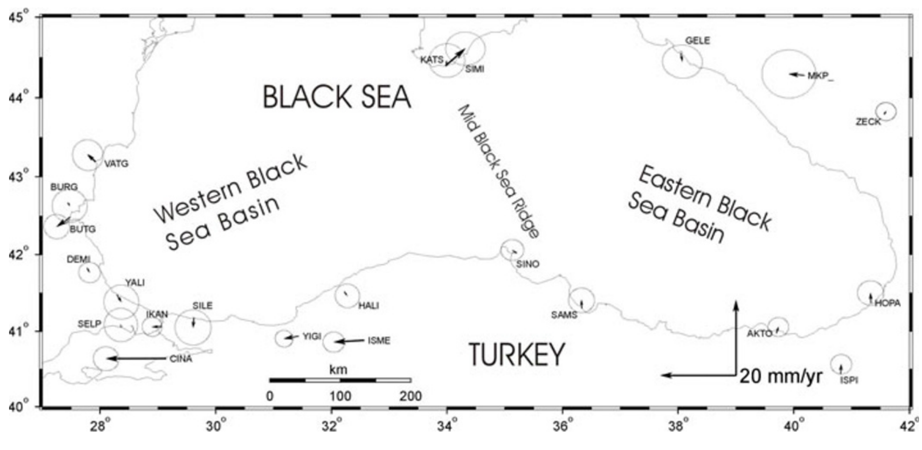

Fig. 2. GPS velocities with respect to Eurasian frame.

garia were observed in 1994 and 1996, most of the network in Bulgaria was observed in 1996 and 1998. Additionally a network in the Caucasus was observed in 1991, 1994, 1996 and 1998 (Table 1) (Reilinger *et al.*, 1997a; Tari, 1999).

4. Black Sea GPS Data Analysis

The GPS data processing has been performed at mainly MIT and partly at ITU by using GAMIT/GLOBK software (Herring, 1998; King and Bock, 1998) in a three-step approach described in Feigl *et al.* (1993) and Dong *et al.* (1998). In the first step, doubly differenced GPS phase observations from each day were used to estimate station coordinates, the zenith delay and the gradients of the atmosphere at each station, and orbital and Earth orientation parameters (EOPs) by applying loose *a priori* constraints to all parameters. In general, 3 or 4 IGS stations are included within this analysis as long as they exist. Hence, the link between regional and global networks is established. Using 3 or 4 global sites in the regional analysis provides enough overlap to resolve the parameters. For initial conditions and non-gravitational parameters for each GPS satellites at a specific time, files from SOPAC are used as well as the ones are computed at MIT for earlier experiments.

In the second step, the loosely constrained estimates of station coordinates, orbits, EOPs and their covariances from each day, formed by survey, were used as quasi-observations in a Kalman filter to estimate a consistent set of coordinates and velocities for a group of survey, which represented

Table 1. Black Sea velocities and one sigma uncertainties with observation history.

Site	Long. (deg.)	Lat. (deg.)	E Rate (mm/yr)	N Rate (mm/yr)	E +− (mm/yr)	N +− (mm/yr)	Correlation	91	92	93	94	95	96	97	98
AKTO	39,702	40,974	0,51	1,66	1,11	1,03	−0,003	X	X		X		X		X
BURG	27,442	42,666	0,47	−0,80	1,89	1,79	−0,011						X		X
BUTG	27,483	42,484	−3,59	−2,53	1,37	1,32	−0,026						X	X	X
CINA	29,143	40,639	−15,85	−0,03	1,38	1,30	−0,027		X		X				X
DEMI	27,779	41,827	0,61	−1,20	1,18	1,10	−0,033		X		X		X		X
GELE	38,049	44,552	0,38	−2,20	2,15	1,80	−0,023						X	X	X
HALI	32,226	41,520	0,79	−1,12	1,32	1,29	−0,026				X		X		X
HOPA	41,339	41,371	−0,14	2,64	1,42	1,33	−0,010				X		X		X
IKAN	29,064	41,064	−2,50	−0,10	1,07	1,04	−0,030		X		X		X		X
ISME	32,570	40,881	−8,06	−0,47	1,16	1,10	−0,011		X		X		X		X
ISPI	40,809	40,437	0,19	2,55	1,13	1,06	−0,009	X					X		X
KATS	33,978	44,396	5,22	4,57	2,13	1,79	−0,011						X		X
MKP_	40,185	44,278	−4,09	0,37	2,92	2,61	−0,006							X	X
SAMS	36,336	41,299	−0,11	2,17	1,40	1,33	0,006				X		X		X
SELP	28,365	41,052	−0,09	0,63	1,80	1,81	−0,012						X		X
SILE	29,623	41,179	−0,23	−2,59	1,95	1,91	−0,008						X		X
SIMI	33,991	44,413	0,14	1,04	1,94	1,82	−0,002						X		X
SINO	35,205	42,020	−1,12	0,79	1,24	1,13	0,002		X		X		X		X
VARN	27,922	43,188	−2,03	1,80	1,66	1,67	−0,034						X		X
VATG	27,920	43,197	−2,03	1,80	1,66	1,67	−0,034						X	X	X
YALI	28,293	41,475	1,13	−1,86	1,88	1,85	−0,017						X		X
YIGI	31,439	40,937	−3,91	−0,68	0,96	0,91	−0,031	X			X		X		X
ZECK	41,565	43,788	0,48	0,76	1,09	0,98	−0,009							X	X

as yearly combination of the relevant experiment set. The global analysis of IGS data are also used as quasi observations. The weights for each data set of quasi-observations are determined by averaging the increments in chi-square per degree of freedom from a forward and backward filtering of data (McClusky *et al.*, 2000).

The reference frame for velocity estimates was defined only at the third step, in which generalized constraints were applied while estimating a 6-parameter transformation (6 components of the rate of change of translation and rotation). Specifically, the departure of the horizontal velocities of 16 stations, from their *a priori* values given by the International Terrestrial Reference Frame 1996 (ITRF96), was minimized to define a realization of Eurasian Frame (Boucher *et al.*, 1998; McClusky *et al.*, 2000). The root mean square (rms) departure of the velocities of the 16 stations after the transformation was 0.5 mm/yr. The estimated velocities were then rotated from no-net-rotation frame of ITRF96 to the Eurasia-fixed frame defined in this research using NUVEL-1A Euler vectors (Table 1) (DeMets *et al.*, 1994; Tari, 1999). The one-sigma uncertainties for the GPS velocities were derived by scaling the formal errors by the square root of chi-square per degree of freedom of the solution. The chi-square per degree of freedom for this solution was 1.07. Velocities of stations with respect to the Eurasian frame are shown in Fig. 2 in which 95% confidence regions are plotted.

5. Conclusions

Velocities show that there is a slight north-south shortening on the eastern half of southern the Black Sea coast, whereas a westward movement can be seen regarding the southwestern coast. However, the magnitudes of the velocity vectors compared with the size of the error ellipses indicate the necessity for further GPS measurements in the region for further confirmation. For example, the magnitudes and directions of KATS and MKP_ sites show that there are some uncertainties related with velocity rate parameters, although it is known that the rates around Caucasus are assumed to vary considerably (Reilinger *et al.*, 1997a). Another outcome is that the North-South motions mostly in the eastern Black Sea are in a few mm/year, while the velocities in the Anatolian region are approximately 10–20 mm/year.

Geological and geophysical evidence including offshore seismic reflection profiles (Finetti *et al.*, 1988), offshore morphology (Meisner *et al.*, 1995), onshore geology and morphology (Okay and Sahinturk, 1997 and references therein), and recent seismic activity (Neprochnov and Ross, 1978; Barka and Reilinger, 1997) support the idea that the compressional tectonic regime is still active in the Eastern Black Sea region. In addition, fault plane solutions of May 20, 1959, July 16, 1963, July 12, 1966, September 3, 1968, and September 3, 1978 earthquakes (Fig. 1) clearly indicate a compressional tectonic regime.

South-west part of the Black Sea do not show important seismic activity to decide whether compressional or tensional regime is active. Although fault plane solution of 30.6.1956 earthquake indicate an extensional regime, this is probably related with the Sredna Gora Graben in the Bulgarian coast. GPS results from this part are scattered and are not enough to state any conclusion for the regional tectonics. More GPS and seismic data will clarify the neotectonic position of this region.

There are uncertainties at the sites located in the northern part of the Black Sea due to the lack of observations. On the other hand, there are no sites in the northern-west part of the region and around the Crimea. More sites and more observation periods will ensure us to resolve the uncertainties and the tectonic behaviour of the whole region.

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